Switchgrass as a biofuels feedstock in the USA

Matt A. Sanderson[1], Paul R. Adler[1], Akwasi A. Boateng[2], Michael D. Casler[3], and Gautam Sarath[4]

[1]*USDA-ARS Pasture Systems and Watershed Management Research Unit, University Park, PA 16802, USA (e-mail: Matt.Sanderson@ars.usda.gov);* [2]*USDA-ARS Eastern Region Research Center, Wyndmoor, PA, USA;* [3]*USDA-ARS Dairy Forage Research Center, Madison, WI;* [4]*USDA-ARS, Grain, Forage and Bioenergy Research Unit, Lincoln, NE, USA.* *Received 30 June 2006, accepted 11 October 2006.*

Sanderson, M. A., Adler, P. R., Boateng, A. A., Casler, M. D. and Sarath, G. 2006. **Switchgrass as a biofuels feedstock in the USA**. Can. J. Plant Sci. **86**: 1315–1325. Switchgrass (*Panicum virgatum* L.) has been identified as a model herbaceous energy crop for the USA. In this review, we selectively highlight current USDA-ARS research on switchgrass for biomass energy. Intensive research on switchgrass as a biomass feedstock in the 1990s greatly improved our understanding of the adaptation of switchgrass cultivars, production practices, and environmental benefits. Several constraints still remain in terms of economic production of switchgrass for biomass feedstock including reliable establishment practices to ensure productive stands in the seeding year, efficient use of fertilizers, and more efficient methods to convert lignocellulose to biofuels. Overcoming the biological constraints will require genetic enhancement, molecular biology, and plant breeding efforts to improve switchgrass cultivars. New genomic resources will aid in developing molecular markers, and should allow for marker-assisted selection of improved germplasm. Research is also needed on profitable management practices for switchgrass production appropriate to specific agro-ecoregions and breakthroughs in conversion methodology. Current higher costs of biofuels compared to fossil fuels may be offset by accurately valuing environmental benefits associated with perennial grasses such as reduced runoff and erosion and associated reduced losses of soil nutrients and organic matter, increased incorporation of soil carbon and reduced use of agricultural chemicals. Use of warm-season perennial grasses in bioenergy cropping systems may also mitigate increases in atmospheric CO_2. A critical need is teams of scientists, extension staff, and producer-cooperators in key agro-ecoregions to develop profitable management practices for the production of biomass feedstocks appropriate to those agro-ecoregions.

Key words: Bioenergy, biomass conversion technologies, *Panicum virgatum* L., stand establishment, switchgrass improvement, USDA-ARS

Sanderson, M. A., Adler, P. R., Boateng, A. A., Casler, M. D. et Sarath, G. 2006. **Utilisation du panic raide comme biocarburant aux États-Unis**. Can. J. Plant Sci. **86**: 1315–1325. Le panic raide (*Panicum virgatum* L.) a été retenu comme herbacée modèle pour la production d'énergie aux États-Unis. Dans cet article, les auteurs mettent en relief certaines recherches courantes de l'USDA-ARS sur cette culture en vue de la production de biomasse. Les recherches intensives sur l'utilisation du panic raide pour la production de biomasse entreprises dans les années 1990 ont considérablement élargi nos connaissances sur l'adaptation des variétés de cette herbacée, sur les méthodes de culture et sur ses bienfaits pour l'environnement. Plusieurs contraintes demeurent néanmoins et nuisent à une production économique de cette plante pour l'obtention de biomasse, notamment des méthodes fiables d'implantation qui feront en sorte que les peuplements soient productifs l'année des semis, une exploitation efficace des amendements et de meilleures techniques pour transformer la lignocellulose en biocarburant. Pour surmonter les contraintes biologiques, on devra recourir à l'amélioration génétique, à la biologie moléculaire et à l'hybridation afin de créer de meilleurs cultivars. De nouvelles ressources génomiques contribueront au développement de marqueurs moléculaires qui permettront la sélection de meilleur matériel génétique. Il faudrait aussi entreprendre des recherches sur les pratiques de gestion profitables qui concourront à la production de panic raide dans les régions écoagricoles et à la découverte de technologies de conversion. Pour l'instant, les biocarburants coûtent plus cher que les combustibles fossiles, mais on pourrait remédier à la chose en évaluant adéquatement les retombées environnementales liées à la culture de vivaces, notamment la lutte contre le ruissellement et l'érosion, une moins grande perte d'éléments nutritifs et de matière organique dans le sol et une meilleure incorporation du carbone dans le sol ou un moins grand usage des engrais et pesticides. La culture de graminées vivaces de saison chaude pour la production de bioénergie pourrait aussi ralentir l'accumulation de CO_2 dans l'atmosphère. On a désespérément besoin d'équipes de scientifiques, de vulgarisateurs et de producteurs coopérants dans les principales régions écoagricoles si l'on veut développer des systèmes de gestion rentables pour obtenir de la biomasse des cultures adaptées à ces régions.

Mots clés: Bioénergie, techniques de conversion de la biomasse, *Panicum virgatum* L., implantation de peuplements, amélioration du panic raide, USDA-ARS

Switchgrass, a native of North American prairies, currently attracts much attention as a model herbaceous energy crop for the USA. Attributes of switchgrass desirable for bioenergy cropping include its demonstrated long-term (> 10 yr) high productivity across many environments (Fike et al. 2006a), suitability for marginal land (Evanylo et al. 2005), relatively low water and nutrient requirements, and positive environmental benefits (Sanderson et al. 1996; Vogel 1996; McLaughlin et al. 2002).

Major constraints for economic bioenergy production from switchgrass include rapid establishment of productive

Abbreviations: **CRP**, Conservation Reserve Program; **EST**, expressed sequence tags stands, achieving greater biomass yields, efficient use of fertilizers, effective harvest and transport systems, and more efficient conversion technologies (Sanderson et al. 2004; Schmer et al. 2006; Vogel et al. 2006). The potential environmental benefits of bioenergy crop production from perennial grasses may add further value if these benefits can be accurately estimated (McLaughlin et al. 2002; Nelson et al. 2006). Environmental benefits include increased soil quality, reduced losses of soil nutrients, recycling nutrients from municipal and agricultural wastes, soil carbon sequestration, and mitigating greenhouse gas emissions (Sanderson et al. 2004; Farrell et al. 2006; Adler et al. 2007).

The Biomass Research and Development Technical Advisory Committee [formed to advise the US Department of Energy (DOE) and US Department of Agriculture (USDA) on program priorities as part of the USA Biomass Research and Development Act of 2000] set a national goal for biomass to supply 5% of the nation's power, 20% of the transportation fuels, and 25% of its chemicals by 2030 (Perlack et al. 2005). This goal will require an annual supply of 907 million Mg (1 billion dry tons) of biomass by 2030. About one-third of this biomass is projected to come from perennial crops such as switchgrass. Achieving these targets will require significant technological advances in plant breeding, biology, and agronomy along with similar advances in conversion technology and issues related to environmental consequences (Koonin 2006; Ragauskas et al. 2006).

Intensive research funded by the DOE in the 1990s laid the foundation for the development of dedicated bioenergy cropping systems based on switchgrass (McLaughlin and Kszos 2005). At the beginning of the 21st century, much of the plant science research on switchgrass as a bioenergy crop shifted to the USDA-Agricultural Research Service (USDA-ARS), which is currently building on that foundation and expanding to other perennial bioenergy crops, cropping systems, and conversion technologies for specific agro-ecological regions of the USA.

There have been several recent reviews of switchgrass for biomass feedstock production (Vogel and Jung 2001; Lewandowski et al. 2003; Sanderson et al. 2004; McLaughlin and Kszos 2005; Parrish and Fike 2005). In this brief review, we selectively highlight current USDA-ARS research on switchgrass for biomass energy and discuss constraints to perennial bioenergy agriculture.

DOE SWITCHGRASS FEEDSTOCK RESEARCH 1980–2002

Initial research on herbaceous energy crops during the 1980s identified switchgrass as the best-adapted herbaceous species across a wide range of environments. Region-specific research, funded by the DOE through the Biofuels Feedstock Development Program at the Oak Ridge National Laboratory, began in 1992. The objectives of that program were "to identify the best varieties and management practices to optimize productivity, while developing an understanding of the basis for long-term improvement of switchgrass through breeding and sustainable production in conventional agro-ecosystems" (McLaughlin and Kszos 2005). McLaughlin and Kszos (2005) detail the research accomplishments from that program. After the expiration of these contracts, research on the plant sciences aspects of switchgrass biomass production shifted from the DOE to the USDA-ARS.

The principal accomplishment of the 10-yr DOE-funded switchgrass program was a projected 25% reduction in biomass production costs (McLaughlin and Kszos 2005). The projected cost reductions resulted from yield increases achieved by: (i) selecting the best adapted cultivar for a region, (ii) optimizing harvest timing and frequency, and (iii) reducing nitrogen fertilizer needs. Evidence of the scientific impact of the DOE-funded switchgrass research is highlighted by the surge in scientific articles related to switchgrass listed in the AGRICOLA data base during 1995 to 2006 (Fig. 1).

Plant breeding efforts funded by the DOE have resulted in the formal release of one new cultivar, Shawnee (Vogel et al. 1996), and several germplasm sources (Tischler et al. 2001; Casler et al. 2006). Many other improved populations have undergone regional or multi-location evaluations (Hopkins et al. 1995a, b; Casler et al. 2004; Casler 2005) and many of these are currently being advanced in seed multiplication for cultivar release. The development of networks of collaborators to facilitate regional uniform testing of switchgrass cultivars and advanced breeding lines is one of the most important legacies of the US-DOE biomass feedstock program.

21ST CENTURY TRANSITION IN SWITCHGRASS FEEDSTOCK RESEARCH: DOE TO USDA-ARS

The plant science research related to switchgrass biomass feedstock production shifted from the DOE to the USDA-ARS in 2002. The goal of the USDA-ARS biomass energy research program is to develop the technology to make biomass energy production systems economically viable by: (i) increasing crop yields and decreasing production costs, (ii) improving ethanol conversion technology, and (iii) genetically altering plants to improve their conversion efficiency to ethanol (USDA-ARS 2006). The national objectives of the program are given in Table 1 and research locations are shown in Fig. 2.

Switchgrass is not the sole focus of energy-crop research in the USDA-ARS. Several other perennial species and biomass sources such as alfalfa (*Medicago sativa* L.), reed canarygrass (*Phalaris arundinacea* L.), bermudagrass (*Cynodon dactylon* L. Pers.), napiergrass (*Pennisetum purpureum* Schumach.), grass seed crop residues, and conservation lands are being investigated for specific agro-ecosystem regions. The following subsections highlight some of the research specific to switchgrass in the USDA-ARS.

Switchgrass Breeding, Genetics, and Molecular Biology

Plant improvement research on switchgrass as a biomass feedstock has proceeded in three phases: (1) germplasm collection and evaluation, (2) new germplasm development by conventional breeding and selection, and (3) molecular

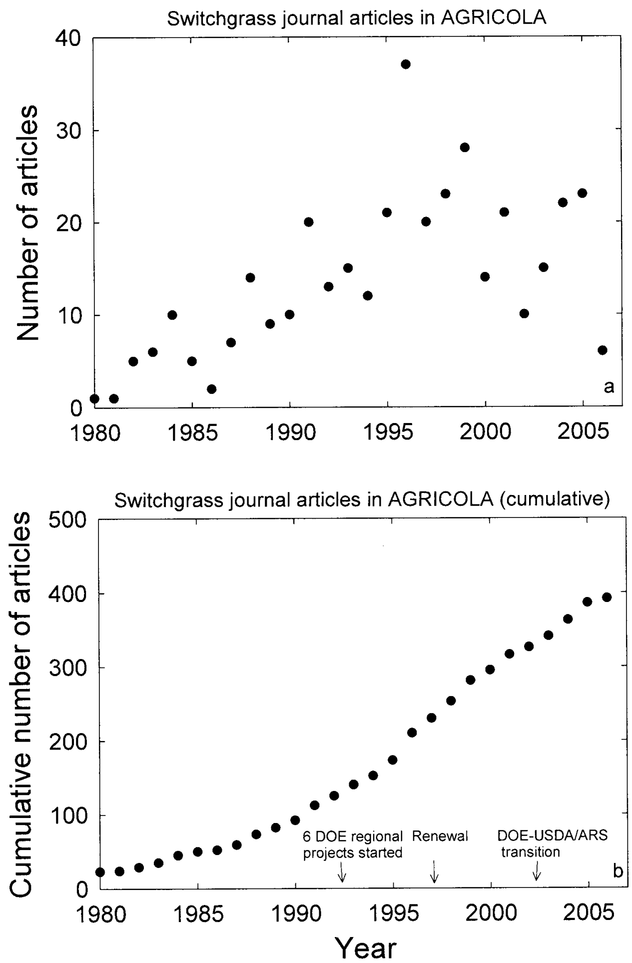

Fig. 1. Number of articles per year (a) and cumulative number of articles (b) on switchgrass listed in the AGRICOLA literature data base.

approaches to improvement. The first phase, funded largely by DOE, has involved evaluation of existing germplasm across much of the historical range of switchgrass in the USA. Multi-location cultivar evaluations have helped to define adaptation zones of existing cultivars, identifying the importance of photoperiod, cold tolerance, and heat tolerance in limiting the breadth of adaptation of most switchgrass cultivars (Sanderson et al. 1999; Casler et al. 2004; Cassida et al. 2005a, b; Fike et al. 2006a, b). These studies have also illustrated the remarkably broad adaptation range of cultivars such as Cave-in-Rock, which has superior biomass production far north and east of its origin (Madakadze et al. 1998; Casler and Boe 2003) but reduced performance in northern dryland environments (Jefferson et al. 2002; Berdahl et al. 2005). Despite the broad adaptation of Cave-in-Rock, most switchgrass cultivars should not be exported more than one hardiness zone north or south of their origin, due to the significant potential for reduced adaptation (Casler et al. 2004; Vogel 2004a).

The second phase of plant improvement, initiated under DOE funding but still continuing, has consisted of collection and evaluation of new switchgrass germplasm, assemblage of breeding populations, and intensive selection for agronomic traits related to biofeedstock production and conversion. Large germplasm collections have been assembled from remnant tall-grass prairie sites. The northern USA has been sampled particularly intensively, due to its lack of representation among most cultivars developed in the 20th century (Hopkins et al. 1995a; Casler 2005). These collections have illustrated a huge level of genetic variability, both within and among these prairie-remnant populations, providing the foundation for breeding populations targeted for USDA Hardiness Zones 3 through 6. Breeding populations have been assembled from these and other switchgrass collections (Casler et al. 2004, 2006) and intensive selection for biomass yield and conversion traits (in some cases) has been underway at four locations: Athens, GA; Stillwater, OK; Lincoln, NE; and Madison, WI. An example of selection progress was illustrated in the genetic shifts created within Kanlow switchgrass, a lowland population originating from near the border of Kansas and Oklahoma. Selection for agronomic traits related to biomass feedstock production in Oklahoma resulted in populations that had higher biomass yield, taller plants, and later heading, making them more southern adapted than the original population (Casler et al. 2004).

Basic genetic research, funded partially by the DOE program, has significantly improved our fundamental knowledge of switchgrass biology and genetics, improving our ability for formulate breeding objectives and strategies. Some of these advancements include identification of cpDNA polymorphisms between upland and lowland switchgrass phenotypes (Hultquist et al. 1996), identification of genetic incompatibility systems and development of

Table 1. Objectives of the USDA-ARS herbaceous biomass energy research program. Locations contributing to task areas are in Fig.2 (USDA-ARS 2006)

Develop improved cultivars, hybrids, and production systems for perennial herbaceous biomass energy crops
Develop improved pre-treatment and fermentation conversion technologies for herbaceous biomass feedstocks
Develop improved methods for assessing and monitoring herbaceous biomass feedstock quality
Develop improved herbaceous biomass harvesting, delivery, and storage technologies
Quantify potential environmental benefits and costs for herbaceous biomass energy production systems
Develop production and conversion information and models that can be used in cost and economic analyses
Evaluate alternative technologies for bioenergy production from biomass

Locations: Peoria, Illinois; Wyndmoor, Pennsylvania; Albany, California; Lincoln, Nebraska; St. Paul, Minnesota; Madison, Wisconsin; El Reno, Oklahoma; Mandan, North Dakota; Tifton, Georgia; University Park, Pennsylvania; Brookings, South Dakota; Corvallis, Oregon; Athens, Georgia.

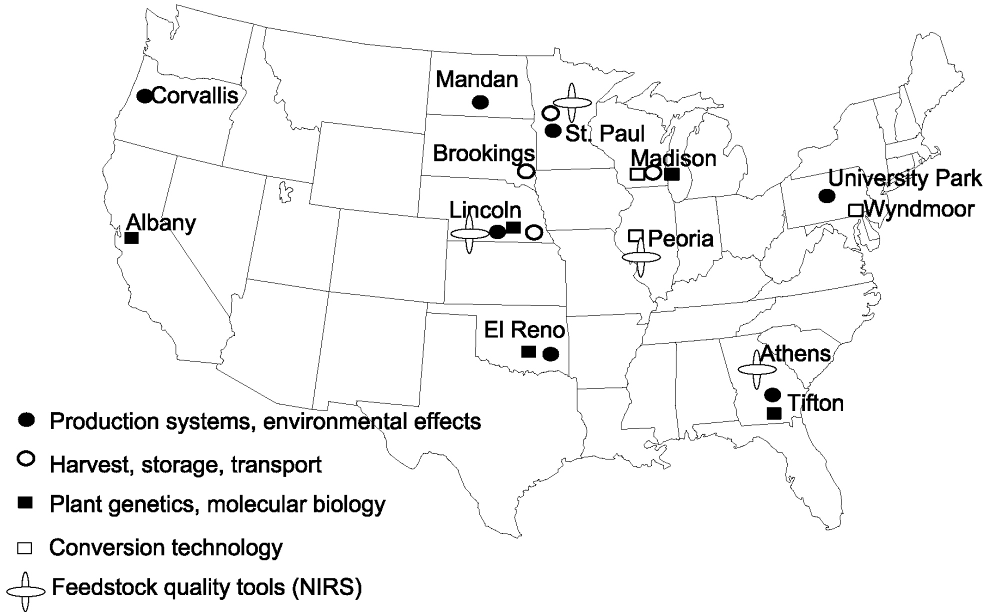

Fig. 2. Location of USDA-Agricultural Research Service switchgrass biomass research locations.

upland × lowland hybrids of switchgrass (Martinez-Reyna et al. 2001; Martinez-Reyna and Vogel 2002), identification of the role of tiller dynamics and phytomer size on seedling development and biomass production of switchgrass (Smart et al. 2004; Boe and Casler 2005), identification of the role of lignification in limiting cellulosic fermentation of switchgrass herbage and its agronomic implications (Casler et al. 2002; Vogel et al. 2002a ; Sarath et al. 2005), and development of somatic embryogenesis for asexual propagation of switchgrass genotypes (Gupta and Conger 1999).

The third phase of switchgrass improvement involves the use of molecular technologies such as genomic and proteomic tools that can complement breeding and management efforts. Switchgrass occurs either as tetraploids or octaploids with an estimated genome size of 3.1 or 6.1 picogram DNA per diploid nucleus respectively (Hopkins et al. 1996), which is about threefold larger than the rice (*Oryza sativa* L.) genome, but smaller than the maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.) genomes. Plastid DNA polymorphisms have been associated with the cytoplasmic-types of switchgrass, the U (upland) and L (lowland) type (Hultquist et al. 1997). Within the same ploidy level, the U and the L types are cross-fertile. Breeding studies have revealed (see above) that switchgrass has less than 1% self-pollination, and this self-incompatibility was similar to the endosperm balance mechanisms found in other plants, indicating that directed crosses can be used to generate marker populations for future analysis. Several single-seed-descent marker populations are in the initial stage of analyses within the USDA-ARS. Based on an RFLP analysis, Missaoui et al. (2005) indicated that a minimum of about 459 markers will be needed to obtain a reasonable first linkage map of switchgrass. Currently available switchgrass cultivars are mostly improved populations of related genotypes (Gunter et al. 2003), therefore, identification of markers will benefit breeding germplasm for the fledgling bioenergy industry.

Functional genomic studies of switchgrass have been initiated primarily within the USDA-ARS (Tobias et al. 2005), and approximately 12 000 expressed sequence tags (EST) have been deposited in the data bases containing about 4000 unique genes. A survey of these genes showed many different classes of physiological gene function were represented in this data base. Many of these genes are involved in the monolignol and cell-wall biosynthesis pathways, and several genic microsatellite sequences with potential for use as markers were also identified (Tobias et al. 2006). These investigations suggest that continued progress can be made to develop marker populations, genomic and EST data bases, as well as biochemical analyses of elite germplasm. Furthermore, the biochemical/genomic analyses of plants generated through divergent breeding for in vitro dry matter digestibility (Sarath et al. 2005) could lead to discovery of markers for traits of significance for conversion.

Switchgrass Production and Management

Biomass production systems research within USDA-ARS focuses on developing best management practices for growing switchgrass in several plant hardiness zones. These include developing economic production-cost information for switchgrass with on-farm field-scale trials (Perrin et al. 2006); identifying the best cultivars on both cropland and conservation lands; improving establishment tools and methods that increase establishment success and reduce establishment costs; and optimizing fertilization and harvest management. In addition to switchgrass production systems, research also addresses the use of Conservation Reserve Program (CRP) lands, buffer strips, wetlands, and grass seed crop residues as potential sites or sources for biomass production.

Environmental Benefits of Bioenergy Production Systems

Environmental benefits associated with perennial bioenergy cropping systems include reduced soil erosion, increased water quality, enhanced soil-carbon sequestration, wildlife habitat, and reduced greenhouse gas emissions. Several USDA-ARS locations are developing information and models to quantify the economics and environmental impact of biomass energy crop production in farm management systems. For example, soils research in the northern Great Plains of the USA showed greater soil organic carbon under switchgrass than cropland (Liebig et al. 2005). The potential long-term storage of soil organic carbon in bioenergy farming systems will depend on the cropping system, how it is managed, and the specific soil.

Bioenergy cropping systems may offset greenhouse gas emissions, but quantifying that offset is complex. Bioenergy crops offset carbon dioxide emissions by converting atmospheric carbon dioxide to organic carbon in crop biomass and soil, but they also emit nitrous oxide and vary in their effects on soil oxidation of methane. Growing the crops requires energy (e.g., to operate farm machinery, produce inputs such as fertilizer), and so does converting the harvested product to usable fuels (feedstock conversion efficiency).

A life-cycle assessment of the net greenhouse gas emissions from bioenergy cropping systems demonstrated that displaced fossil fuel was the largest greenhouse gas sink followed by soil carbon sequestration (Adler et al. 2007). Nitrous oxide emissions were the largest greenhouse gas source. All cropping systems simulated provided net greenhouse gas sinks compared with the fossil fuel life cycle, even in the long-term when there were no further increases in soil carbon sequestration due to the reaching a new steady state with carbon inputs. Switchgrass and hybrid poplar (*Populus* spp.) provided the largest net greenhouse gas sinks, greater than 200 g carbon m^{-2} yr^{-1} for biomass conversion to ethanol, and greater than 400 g carbon m^{-2} yr^{-1} for biomass gasification for electricity generation (Adler et al. 2007). Compared with the life cycle of gasoline and diesel, ethanol and biodiesel from dedicated energy crops reduced greenhouse gas emissions by 35–40% for corn rotations, 85% for reed canarygrass, and more than 115% for switchgrass and hybrid poplar (Adler et al. 2007).

The use of biofuel will reduce the net emission of greenhouse gases associated with fossil energy use, whether from production and use of liquid fuels or generation of electricity from gasification of biomass (Adler et al. 2007). The choice of crop and management practices will affect the net greenhouse gas emissions from biofuel. Cellulosic energy crops such as switchgrass have the greatest potential to reduce the net greenhouse gas emissions associated with fossil energy use in the near- and long-term. Carbon credit markets associated with greenhouse gas mitigation strategies have been developed (McCarl and Schneider 2001; Paustian and Babcock 2004). Short-term strategies for mitigating greenhouse gases using biofuels include soil-carbon sequestration, but displacement of greenhouse gases associated with the use of fossil fuels are the only long-term mitigation mechanism when using biofuels and would be easier to track for carbon markets (Adler et al. 2007).

Research on the environmental effects of bioenergy cropping is linked with another USDA-ARS national initiative on greenhouse gas reductions termed GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network; Jawson et al. 2005) to compare various greenhouse gas mitigation strategies in several agroecoregions in the USA. Results from the environmental research program will be the key to informing public policy on valuing the net positive externalities of bioenergy crop production (Conway and Erbach 2004).

Feedstock Assessment Research

Bioconversion facilities will need rapid methods to assess feedstock quality so that processes can be optimized for specific feedstocks and end products. Research on feedstock assessment includes evaluating the in vitro digestion assay to estimate ethanol yields (Weimer et al. 2005); developing feedstock quality assessment technologies such as near infrared reflectance spectroscopy (NIRS); and generating standards that can be used in genetics, management, and conversion research (Dien et al. 2006).

Conversion Technologies

Current conversion technologies under development are grouped under two basic methodologies. The first is the sugar conversion approach that makes use of cereal grains, lignocellulosic materials such as switchgrass and other biomass and crop residues such as corn stover as feedstocks for ethanol production via saccharification and fermentation processes. The second approach is thermochemical conversion that involves thermal degradation (pyrolysis) to obtain bio-oils (or pyrolysis liquids), and simple combustion of the biomass "as is." Syngas, which is rich in hydrogen and carbon monoxide, can be synthesized to mixed alcohols by the Fischer Tropsch liquids process.

Because of the immense interest in developing alternative transportation fuels in the USA, most of the research effort is placed on the sugar conversion technologies with the vision of establishing facilities that will produce biofuels and chemicals. Other technologies, including thermochemical conversion, have attracted little interest and funding recently, despite the fact that this approach is widely received elsewhere in the world and offers near-term opportunities. This notwithstanding, the synergy between the sugar and the thermochemical conversion approaches cannot be underestimated. Unlike corn, waste streams associated with lignocellulosic biomass biorefinery process, such as the lignin-rich residues from a biomass-to-ethanol plant may have little nutritional value or market but can be a potential source of the needed thermal energy that would otherwise come from the use of fossil fuels. For example, some ethanol plants are currently installing fluidized bed boiler systems that burn biomass residues as means to reduce the need for natural gas.

CONSTRAINTS TO SWITCHGRASS PRODUCTION AND USE IN BIOENERGY SYSTEMS

The principal constraints to economic and energetically efficient switchgrass production for bioenergy include reliable and economic establishment techniques, achieving greater biomass yields through plant improvement and improved management, and efficient fertilization and harvest management (Sanderson et al. 2004; Schmer et al. 2006; Vogel et al. 2006). Conservation lands have been suggested as sources of biomass feedstock (Smith 2004); however, there are important questions about the suitability of these lands for biomass production. Other constraints include technological challenges in conversion methods. In this section we briefly review these limitations and their potential solutions.

We recognize that there are other constraints in the entire life-cycle of bioenergy production including transportation and storage issues (Cundiff 1993) along with issues related to building and locating conversion facilities (Wright 2006) and energetics (Farrell et al. 2006; Morrow et al. 2006; Wu et al. 2006). However, we do not address these issues in this brief review.

Switchgrass Improvement

Developing improved cultivars of switchgrass is critical to the economic success of future bioenergy cropping systems. Cultivars with increased biomass yields are an obvious goal, but value-added traits will also require significant attention of plant breeders and geneticists. Continued intensive selection within breeding populations is expected to increase biomass yields, as observed in previous selection experiments (Vogel 2004a). In addition, hybrids between a limited number of upland and lowland genotypes have demonstrated potential to increase biomass yields by up to 18% (Vogel 2004b). Increased efforts to identify heterotic combinations of upland and lowland genotypes, combined with intrapopulation improvement within both upland and lowland populations will improve the economic potential of switchgrass hybrids. Switchgrass plants with superior hybrid combining ability can be asexually propagated by somatic embryogenesis, providing a mechanism for large-scale propagation of hybrid seed production fields for superior two-clone hybrids (Gupta and Conger 1999).

Reduced lignification will be an important objective for improving conversion of switchgrass biomass to energy, as lignin inhibits both glucose recovery from biomass pretreatments (Dien et al. 2006) and cellulosic fermentation (Vogel and Jung 2001). Lignin can be reduced by conventional selection and breeding, genetic transformation, or a combination of both tools (Casler and Vogel 1999). Although silica and other minerals can cause significant problems for combustion of switchgrass hay or pellets, there has been little effort to breed for reduced amounts of these minerals. Samson et al. (2005) recommend breeding for increased stem:leaf ratio and reduced leaf surface area to reduce both the potential for uptake of silica from the soil and deposition on leaf surfaces. Finally, more rapid and improved establishment capacity is an important goal for switchgrass breeding, although attempts to improve this by selection for high shoot mass have not yielded significant improvements in seedling establishment under optimal establishment conditions (Smart et al. 2003). These authors speculated that development of selection criteria to improve root growth of seedlings might result in improved establishment capacity.

Developing "optimal" genotypes for biofuels production will be dependent on the conversion technology (i.e., thermochemical or fermentation) that will ultimately be used. For example, high lignin concentration would be a negative trait for switchgrass destined for fermentation to ethanol, but could be a positive trait for biomass used for thermochemical conversion. Having access to markers and knowledge of switchgrass functional genomics (both proteins and genes) will be crucial for rapid identification of elite germplasm for different conversion technologies. Based on current breeding cycles, it takes about 10 yr to develop a new switchgrass cultivar. Marker-assisted selection, however, could speed up this process. Of note is the imminent large-scale sequencing of switchgrass ESTs by the Joint Genome Institute set to begin in late 2006 (Dr. Christian Tobias, USDA-ARS, personal communication to G. Sarath). This project should yield a comprehensive cataloging of genes that are specific to unique stages of plant development, and can result in the development of many useful markers as well as identification of more specific and targeted gene-selection strategies.

A major short-term focus is to develop switchgrass cultivars for conversion into liquid fuels, principally as ethanol. From a feedstock perspective it is recognized that "one size does not fit all" and there will be need to develop different species for different geographic zones in the USA. Principal components sought after in feedstocks are high yields, sustainability of production, and maximal returns to producers.

Establishment of Switchgrass

Obtaining adequate yields of switchgrass in the year of seeding requires rapid establishment of a dense stand and enough time to accumulate biomass (Perrin et al. 2006; Vogel et al. 2006). Based on the frequency grid method, a tool developed by the USDA-ARS to estimate stand density (Vogel and Masters 2001), a stand frequency level of 40% or greater was necessary for establishment success of switchgrass and biomass production in the following years in the northern Great Plains of the USA (Schmer et al. 2006). Typical difficulties with achieving the recommended stand densities during switchgrass establishment include seed dormancy or poor seed quality, improper or nonuniform planting depth, lack of weed control options at establishment, and variable weather and soil conditions. An excellent in-depth discussion of these problems and their potential solution is in Parrish and Fike (2005).

Techniques considered for improving establishment of switchgrass include: appropriate planting dates (Panciera and Jung 1984; Vassey et al. 1985); seeding rates (Vassey et al. 1985; Vogel 1987); seed scarification or stratification (Tischler et al. 1994); selection for reduced mesocotyl elongation in seedlings (Tischler et al. 2001) and reduced seed dormancy (Ocumpaugh et al. 2003); herbicides (Wolf et al. 1989); and interplanting switchgrass with row crops (Hintz et al. 1998).

Switchgrass seed germination is temperature and pH sensitive (Hanson and Johnson 2005), but some level of dormancy exists even in cold-stratified seeds. This dormancy in stratified seeds can be overcome by external sources of nitric oxide (Sarath et al. 2006).

Weed competition during switchgrass establishment can severely limit achieving economic yields in the first year. Chemical weed control options for the establishment period are lacking. Quinclorac (3,7-dichloroquinoline-8-carboxylic acid) is a relatively new herbicide for switchgrass establishment that may have utility in many regions (Schmer et al. 2006). Proper crop selection in the year preceding establishment can reduce weed competition with switchgrass seedlings. Little scientific information exists, however, on which crops to use the year before planting switchgrass. Genetically enhanced crops such as glyphosate [N-(phosphonomethyl)glycine]-resistant corn and soybean [*Glycine max* (L.) Merr.] enable use of a nonselective herbicide to control many weeds in the year before switchgrass establishment.

Nitrogen Fertilizer Use

Nitrogen fertilizer use must be optimized in biomass feedstock production because of the economics and energy costs associated with fertilizer production and application. Recommendations for nitrogen fertilization of switchgrass for biomass feedstock production vary greatly among agroecoregions because of variation in soils, crop management, and weather (Parrish and Fike 2005).

Nitrogen cycling within the grass plant also affects N fertilizer management. Warm-season grasses internally recycle N from the above-ground shoots to the crown and roots in the fall for use in over wintering and regrowth the following spring (Clark 1977). This mechanism enables an efficient use of nitrogen by the plant. Internal cycling and storage of nitrogen within the switchgrass plant may contribute to its conservative nitrogen use. About 18% of the annual nitrogen demand of big bluestem (*Andropogon gerardii* Vitman) and indiangrass (*Sorghastrum nutans* L.) on native prairie was supplied by internal reserves (McKendrick et al. 1975). There is some evidence for the recycling mechanism in switchgrass (Parrish and Fike 2005). A management practice to exploit this N recycling mechanism would be to harvest switchgrass once at the end of the season to lower nitrogen concentrations in the biomass and reduce nitrogen removal from the system, thereby increasing nitrogen-use efficiency (Parrish and Fike 2005) However, there are no quantitative, long-term data in the literature to support this mechanism. It is not clear when nitrogen recycling occurs, how much nitrogen is recycled, and how it contributes to the nitrogen economy of a biomass energy crop. We also do not know how much recycled nitrogen is reused the following year, or how N fertilizer and timing affect recycling and reuse. This information is essential for understanding how to improve nitrogen-use efficiency and to develop site-specific soil test and fertilizer guidance.

Harvest Management

Harvest management of switchgrass can greatly affect biomass yield and chemical composition. A single harvest in the fall has been recommended for maximum biomass yields in the southcentral US (Sanderson et al. 1999). Research in Quebec, Canada, also showed that a single fall harvest maximized switchgrass yield (Madakadze et al. 1999). Harvest management may vary with cultivar. Highest biomass yields were obtained with a single fall harvest for lowland cultivars, whereas upland cultivars yielded more biomass harvested twice yearly in the upper southeastern region of the USA (Fike et al. 2006b). Ash and other mineral concentrations in warm-season grasses typically decline with maturity (Sanderson and Wolf 1995; Madakadze et al. 1999). Thus, delaying harvest of the grass crop to late maturity stages would minimize the concentrations of inorganic elements in the feedstock.

In the midwestern USA, maximum switchgrass yields occurred when harvested in mid-August (Vogel et al. 2002b); yields decreased 10 to 20% with harvests after a killing frost in October. Other studies have documented reduced stand persistence with a single summer harvest (Casler and Boe 2003; Mulkey et al. 2006; Adler et al. 2006). Delaying harvest until spring in the northeastern USA reduced moisture concentration (from about 350 to 70 g kg^{-1}) to safe storage levels; however, switchgrass yields decreased almost 40% (Adler et al. 2006). A mid-August harvest would be able to meet the water concentration requirements for stable storage with field drying; however, twice the amount of nitrogen would be removed with harvest and other minerals are also higher. About 10% of the yield reduction during winter resulted from decreases in tiller mass; however, almost 90% of the yield reduction was due to an increase in biomass left behind by the baler (Adler et al. 2006). Improvements to harvest machinery to reduce these losses would make spring a very desirable time to harvest because of high biofuel quality and scheduling during a time when other farm operations are minimal. Spring harvest could allow over-winter wildlife cover and, if properly timed, would not interfere with bird nesting behavior.

Use of Set-aside Lands for Biomass Feedstock

Land in the CRP (a land set-aside program established by the USA Food Security Act of 1985) may be a potential, readily available supply of biomass feedstock (Smith 2004). The goal of the CRP is to remove land from crop production and plant long-term resource-conserving vegetation cover to prevent soil erosion, improve water quality, and enhance wildlife habitat. In the US there are 14 million ha of CRP (USDA Farm Service Agency 2006). Important considerations include whether these lands are suitable for biomass production, what management is needed, and whether or not biomass production will compromise any environmental benefits of these set-aside programs.

In a survey of CRP lands in Minnesota established according to the NRCS CP-2 recommendations (use of native grasses and no herbicides), Jewett et al. (1996) reported that switchgrass was planted in 100% of the CP-2 fields. Switchgrass persisted on 94% of the fields planted and generally exceeded 50% ground cover on all sites.

Adler et al. (2005) surveyed 34 sites across the northeast USA that included CRP, wildlife habitat improvement program (WHIP), mine reclamation, and other conservation lands as a resource assessment for biomass production. Aboveground biomass at these sites averaged 6.6 Mg ha^{-1}. More than 280 plant species were identified across all sites with an average species richness of 34 species per 0.1 ha (range of 12 to 60 plant species). The top five native plant species accounted for more than 65% of plant cover. Aboveground biomass decreased with greater species richness but increased with percentage cover of switchgrass, big bluestem, and indiangrass.

Mulkey et al. (2006) studied the response of switchgrass-dominated CRP sites to various nitrogen and harvest management alternatives in South Dakota. They recommended that applying < 112 kg nitrogen ha^{-1} during the growing season and harvesting once annually after a killing frost were appropriate management practices to optimize biomass production on these sites.

Because switchgrass is a perennial with a low requirement for nutrient inputs, CRP lands could be harvested for biofuel and maintain benefits to water quality and reduced soil erosion. However, its value as wildlife habitat will depend on management and desired resident wildlife species. Harvest frequency and timing will affect vegetation structure, and consequently desirability of habitat will vary depending on target species. Harvest can improve habitat for some species (Roth et al. 2005); however, increasing vegetation stand density to improve switchgrass yields may reduce the habitat quality for some species. Wildlife habitat must be valued to assist farmers in making decisions on the trade-off between biomass yield and improved habitat value for certain target avian species.

Conversion Technologies and Constraints

Because of the large variability in lignocellulosic biomass composition, the industry may require different pretreatments, chemical processes, and enzymes for hydrolysis of the biomass polysaccharides into fermentable sugars and use of recombinant organisms that can ferment C5 and C6 sugars to ethanol. On the thermochemical side, pyrolysis, the first step in the gasification process is an endothermic reaction that requires heat. This may affect the net energy recovered depending on the efficiency of the thermal system. For biomass conversion via the sugar conversion approach, it is well known that cellulose conversion can be adversely affected by hemicellulose and lignin (Chang and Holtzapple 2000). On the other hand, lignin is known to improve thermochemical energy conversion efficiency (Boateng et al. 2006)

Fermentation

As mentioned earlier, large variations in biomass feedstock composition may require different enzymes or chemical processes. Research is underway at USDA-ARS to overcome some of the constraints associated with conversion technologies. Dien et al. (2006) have investigated chemical composition and response to dilute-acid pretreatment and enzymatic saccharification of various energy crops being developed within the USDA-ARS including switchgrass at various maturity levels. Switchgrass had more carbohydrates on a weight basis than alfalfa or reed canarygrass. Yields of potentially fermentable sugars depend on both variations in carbohydrate composition and their release efficiency via dilute acid/enzymatic saccharification conversion process (Dien et al. 2006). These authors found that, overall, the carbohydrate contents increased with switchgrass maturity. However extracting glucans becomes more challenging with increasing plant maturity, hence the need to increase pretreatment severity to compensate for maturity. Doing so however, might lower the yields of hemicellulose sugars.

Thermochemical

Boateng et al. (2006) conducted pyrolysis of Cave-in-Rock switchgrass harvested at three stages of physiological maturity in an analytical pyrolyzer coupled with a gas chromatograph/mass spectrometer (PY-GC/MS) system at 600 through 1050°C. They analyzed the pyrolysis yields in terms of char and two sets of gas i.e., non-condensable gas comprising mainly carbon monoxide, carbon dioxide and low molecular weight hydrocarbons such as methane and condensable gas consisting of acetaldehyde, acetic acid and higher molecular weight compounds (Fig. 3). The general conclusions of this study indicate that plant maturity determined by the physiological stages of switchgrass development plays an important role in the pyrolysis of switchgrass. To maximize the synthetic gas yield, allowing the plant cell walls to mature by harvesting late is beneficial. The gas quality at atmospheric conditions estimated by heat of combustion also improves with maturity. To maximize condensable gases (which can be refined to pyrolytic oils and chemicals), later maturity may also be beneficial, especially, when produced at pyrolysis temperatures lower than 900°C. The kinetics of the pyrolysis reaction was related to maturity, showing a linear increase in activation energy for gas decomposition from the vegetative, anthesis and senescent stages of maturity.

CONCLUSIONS

Switchgrass has received much study for biomass feedstock production and conversion through research funded by the DOE and USDA during the past two decades. This research has significantly increased our knowledge of the biology and agronomy of switchgrass. We have an improved understanding of the adaptation of existing cultivars and the development of new cultivars with improved yield and adaptation ability for different agro-ecoregions. Recent research on production practices, such as establishment and harvest management, is fine-tuning our knowledge. Still, there remain several constraints to switchgrass use in bioenergy cropping systems, including reliable establishment methods to obtain productive stands in the first year, targeted fertilization and nutrient management techniques for efficient use of nitrogen fertilizer, and highly efficient methods to convert lignocellulose to ethanol and other products. Current research on the genetics, breeding, and molecular biology of switchgrass will result in new switchgrass cultivars with improved yield, greater establishment ability, and altered cell-wall properties for more efficient conversion.

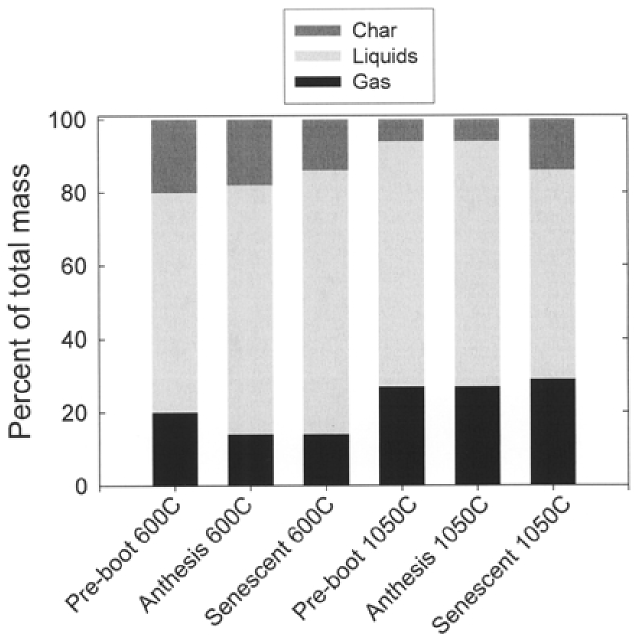

Fig. 3. Switchgrass pyrolysis yields at two temperatures (600°C and 1050°C) as a function of plant developmental stage. Data extracted from Boateng et al. (2006).

A national bioenergy strategy will require multiple sources of biomass and multiple biomass crops for specific agro-ecoregions. A critical need is teams of scientists, extension staff, and producer-cooperators in key agro-ecoregions to develop profitable management practices for the production of biomass feedstocks appropriate to those agro-ecoregions. Switchgrass may be the first among many perennial feedstocks for the emerging lignocellulosic energy industry in the USA.

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